Renewable and Sustainable Energy Reviews 39 (2014) 1–13

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

The use of phase change materials in domestic heat pump and air-conditioning systems for short term storage: A review

Pere Moreno, Cristian Solé, Albert Castell*, Luisa F. Cabeza

GREA InnovacióConcurrent, Universitat de Lleida, Edifici CREA, Pere de Cabrera s/n, 25001 Lleida, Spain

ARTICLE INFO

Article history:
Received 5 August 2013
Received in revised form
22 May 2014
Accepted 7 July 2014
Available online 26 July 2014

Keywords:
Heat pump
Air-conditioning
Thermal energy storage
Phase change materials
Space heating and cooling

ABSTRACT

Heat pumps for space heating and cooling are a mature and highly efficient technology that can take advantage of renewable energies. They can also provide energy savings by load shifting when they operate together with thermal energy storage (TES). This paper presents a literature review of TES systems using phase change materials (PCM) potentially applicable to domestic heat pumps used in residential and administrative buildings. The paper describes the systems proposed by the different authors and presents the main conclusions of the studies. The TES systems presented are not only used as energy storage to shift the load demand but also for other applications such as heat recovery or defrosting in air-conditioners. The PCM have the suitable melting temperature to work together with standard heat pumps in each application. Moreover, some systems where the heat pump is coupled to latent heat thermal energy storage (LHTES) units and other energy sources or where the TES system is incorporated in a radiant floor or air distribution system have also been included.

Contents

1. Introduction . . . 1
2. PCM storage in heat pumps for space heating . . . 2
   2.1. Thermal energy storage within the heat pump cycle . . . 2
   2.2. PCM energy storage as defrosting solution . . . 3
   2.3. Hybrid systems for space heating . . . 5
3. PCM storage in heat pump for space cooling . . . 7
   3.1. Thermal energy storage within the air-conditioning cycle . . . 7
   3.2. PCM energy storage as heat recovery . . . 8
   3.3. Hybrid systems for space cooling . . . 10
4. Conclusions . . . 11
Acknowledgements . . . 13
References . . . 13

1. Introduction

Buildings represent 40% of the European Union's final energy consumption [1]. In residential homes, two thirds of this consumption is for space heating, which means that a large energy saving potential remains untapped [2]. Heat pumps technology is presented as candidate technology to achieve high energy savings since it is included in the Directive on the promotion of the use of energy from renewable sources (2009/28/EC) as an environmentally friendly technology [3].

Heat pumps use renewable energy from their surroundings (ambient air, water or ground) and "high-grade" energy, e.g. electricity or gas, to raise the temperature for heating or to decrease it for cooling. If certain criteria are met, the European Union credits heat pumps as using renewable energy. They achieve point-of-use efficiencies greater than 100%, i.e. they provide more

* Corresponding author. Tel.: +34 973 00 35 70.
E-mail address: acastell@diei.udl.cat (A. Castell).

http://dx.doi.org/10.1016/j.rser.2014.07.062
1364-0321/

useful cold or heat (in energy terms) than the electricity input. The heat pump cycle can be used for space heating or cooling; reversible systems can alternate heating and cooling, while hybrid systems (for instance those that couple heat pumps with conventional boilers or solar thermal collectors) can provide heating and cooling simultaneously. Heat pumps for space and water heating are mature technologies, but their share of the global heating market is small [4]. In Europe, the heat pump sales underwent negative growth the last years, in part, due to the global financial crisis. However, the initial recovery of the market was observed since sales in 2011 finished on par with 2010 results (Fig. 1) [5].

The International Energy Agency (IEA) includes the heat pumps for space heating and cooling and hot water as one of the technologies which has the greatest long-term potential for reducing CO_2 emissions. According to the proposed BLUE Map scenario (a scenario in which energy-related CO_2 emissions are reduced by 50% in 2050 from 2007 levels), it is estimated that heat pumps will dramatically increase their share of space and water heating. The total number of installed units at global level in the residential sector for space heating and cooling and hot water is estimated to reach almost 3.5 billion by 2050, which involves a CO_2 emissions reduction of about 1.25 $GtCO_2$ [4].

In recent years, the number of air-conditioning systems in southern European countries has severally increased. This creates considerable problems at peak load times, increasing the cost of electricity and disrupting the energy balance in those countries. Therefore, priority should be given to strategies which enhance the thermal performance of buildings during the summer period [6].

The use of thermal energy storage (TES) systems for thermal applications such as space and water heating, cooling, or air-conditioning has received much interest since it is considered to be one of the most promising solutions to correct the mismatch between supply and demand of energy. TES systems give the opportunity to shift the load demand from high-cost energy period to off-peak period meeting the thermal loads that occur during high-demand. In addition, the purchase of additional equipment for heating, cooling, or air-conditioning applications can be deferred and the equipment sizing in new facilities can be reduced. The equipment can be operated when thermal loads are low to charge a TES systems and energy can be withdrawn from the storage to help meeting the maximum thermal loads that exceed the equipment capacity [7].

Moreover, TES systems provide environmental advantages by using electricity produced at night, when utilities are generally operating their most efficient plants. As a result, significant savings of primary energy sources (coal, natural gas, oil or nuclear fuel) accrue to electric utilities and reduce pollutant emissions [8]. In Europe, it has been estimated that around 1.4 million GWh per year could be saved and 400 million tonnes of CO_2 emissions avoided in the building and industrial sectors by more extensive use of heat and cold storage [9].

Latent heat thermal energy storage (LHTES) using phase change materials (PCM) present the advantage of operating within small temperature ranges and, at the same time, accumulating large amounts of heat or cold comparing to sensible storage. In fact, PCM can store about 3–4 times more heat per volume than is stored as sensible heat in solids or liquids in a temperature interval of 20 °C [10] Combining PCM LHTES with heat pumps is a promising technology which can lead to take advantage of both technologies for energy savings and environmental benefits.

This paper reviews the use of LHTES systems when coupled to domestic heat pumps for space heating and cooling. The described TES systems are not only used as energy storage to shift the load demand but also for other applications such as heat recovery or defrosting in air-conditioners. Moreover, some studies have incorporated the energy storage in a radiant floor or air distribution system. The paper presents first those systems studied for space heating and later those for space cooling.

2. PCM storage in heat pumps for space heating

2.1. Thermal energy storage within the heat pump cycle

Few studies are found in the literature about the use of PCM storage tanks included in heat pump systems for space heating. In these systems, the exhaust heat produced by the condenser of the heat pump is used to heat up a heat transfer fluid (HTF), such as water, which is used for heating applications. Hamada and Fukai [11] (Japan) analysed an experimental set-up where the condenser of a heat pump was connected to two different PCM storage tanks and the evaporator was connected to an ice storage tank so that the system provides heating and cooling. The study was focused on the heat transfer improvement of the TES tanks and the results were compared to a three dimensional heat transfer model evaluated in a previous study [12]. The flow diagram of the experimental set-up is shown in Fig. 2. During the night the heat pump supplies cold to the ice storage tank using night time power. Hot water, heated by the exhaust heat of the heat pump, is simultaneously pumped into tanks A and B. Paraffin wax with a melting temperature near 49 °C and 180 kJ/kg as latent heat is used in both tanks to store heat. The tanks (2.29 m width × 4.55 m length × 2.05 m height) are shell and tube

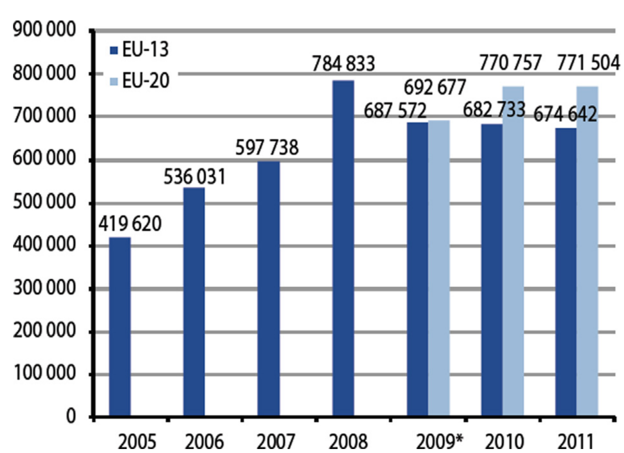

Fig. 1. Development of heat pumps sales from 2005 to 2011 in EU [5].

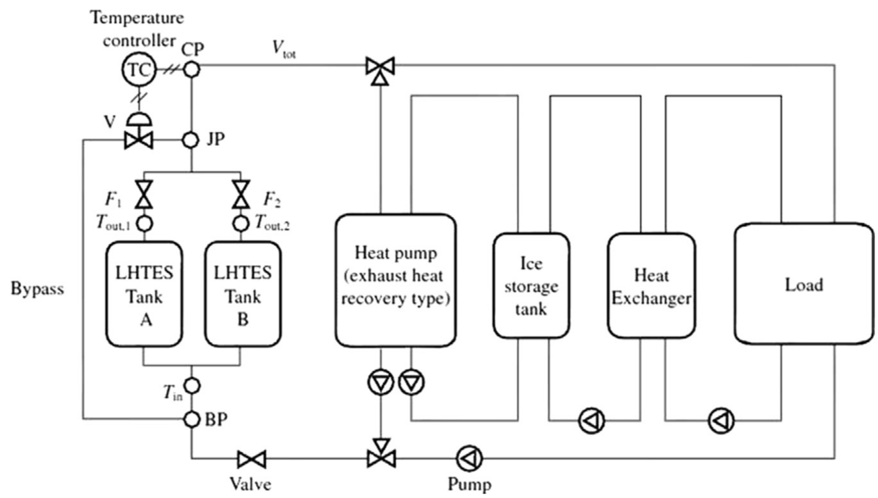

Fig. 2. Flow diagram of the experimental set-up studied by Hamada and Fukai [11].

heat exchangers where carbon fibre brushes are used to enhance the heat transfer between the heat transfer fluid and the paraffin wax. The study analysed the effect of including the carbon fibre brushes in the TES tanks comparing experimental and numerical results. The corrected model, which is modified from the original by choosing the diameter of the brushes as an empirical parameter, predicted well the thermal outputs of the tanks under various experimental conditions. The authors concluded that the brushes remarkably improve the thermal outputs of the thermal energy storage tanks, resulting in reduction in cost and space. However, the effect of the inclusion of the PCM storage tanks in the heat pump system was not discussed in this study.

Agyenim et al. [13] (UK) evaluated the behaviour of a PCM thermal energy storage system to be coupled to a heat pump as part of a wider study to investigate a suitable PCM to take advantage of off-peak electricity tariff. The heat transfer characteristics, according to different inlet HTF temperatures, of a 1.2 m long longitudinally finned copper cylinder filled with 93 kg of RT58 were evaluated in this study. The potential implications of integrating the PCM storage unit to an air source heat pump to meet 100% residential heating energy load for a common building in UK were also assessed. The results showed that due to the low thermal conductivity of the PCM, after 7 h of charging, only 52% of the theoretical maximum energy was available (62.9 °C as inlet HTF temperature) and the average store tank size needed to cover 100% daily heating of a semidetached house was 1116 l. Moreover, a quadratic relationship between the heat transfer coefficient and the inlet HTF temperature was found. Similarly to Hamada and Fukai [11], Agyenim et al. [13] also concluded that an improvement on the heat transfer could lead to reduce the store size. They quantified this reduction by 30%.

Considering that modern low temperature heating systems for buildings need a supply temperature of approximately 35 °C, Leonhardt and Müller [14] (Germany) developed a thermo-hydraulic model of a PCM storage coupled to a heat pump. Fig. 3 shows the schematics of the system.

The model of the system was implemented in Modelica software. The PCM used for the simulations was a theoretical material based on typical paraffin with a phase change temperature and enthalpy of 46.8 °C and 180 kJ/kg, respectively. The latent heat storage unit was composed by PCM plates flowed by water, and 170 kg of PCM was considered.

The results presented a comparison between sensible heat storage and the PCM unit when coupled to a heat pump system. The main conclusion of this study was that the switching between on and off of the heat pump was reduced when a PCM storage unit instead of a sensible heat buffer was used; this means that the heating costs can be spared. However, no experimental validation of the model was performed.

2.2. *PCM energy storage as defrosting solution*

Most of the studies using PCM in air-conditioning are focused on solving the frosting problem by adding a storage device within the refrigeration cycle. Frost formed on the outdoor coil appears when an air source heat pump (ASHP) operates for space heating with external low ambient temperatures in winter. The frost formed reduces the air passage area of the outdoor coil acting as a thermal insulator. As a result, the performance decreases drastically and the ASHP can even be shutdown. Currently, the most widely used standard defrosting method for ASHPs is reverse-cycle defrost. When a space heating ASHP unit is operated at a reverse-cycle defrost mode, its outdoor coil acts as a condenser and the indoor coil as an evaporator. Also, during defrosting, the indoor air fan in an ASHP unit is normally switched off to avoid blowing cold air directly to the indoor space, affecting the thermal comfort of the occupants. The studies presented next try to solve these problems by using PCM systems for defrosting the outdoor coil.

Daikin Industries Ltd. (Japan) put on the market a latent TES system integrated into the heat pump for defrosting in 1989 [15]. In this TES system the PCM, polyethylene glycol, which surrounded a rotatory compressor, was used to store the waste heat released by the compressor through a finned-tube heat exchanger. This system was used during start-up and during defrosting. During start-up, the TES reduced the time required to reach a 45 °C discharge air temperature by 50%. During defrosting, a heating capacity of 3.5 kW was made available by the TES, which avoided a drop in room temperature. Integrating the system improved the heating capacity by about 10% and the COP by 50%.

Jiankai et al. [16] (China) experimentally studied the use of PCM for heat pump defrosting. They compared the use of a PCM heat exchanger enclosed in the refrigeration cycle with the normal defrosting method of the air-source heat pumps (ASHPs), which is the reverse cycle defrosting method. The experimental set-up diagram and the PCM heat exchanger are shown in Fig. 4. The PCM used was $CaCl_2 \cdot 6H_2O$ mixed with $SrCl_2 \cdot 6H_2O$ (2% of the mass fraction) in order to decrease the degree of subcooling of the refrigerant to 0 °C. The heat exchanger contained 1.9 L of PCM.

The experiments were carried out using three different operational modes according to the position of the PCM heat exchanger with respect to the indoor coil. Thus, the operational modes were: series defrosting, parallel defrosting and single defrosting. The modes were run by changing the valves position.

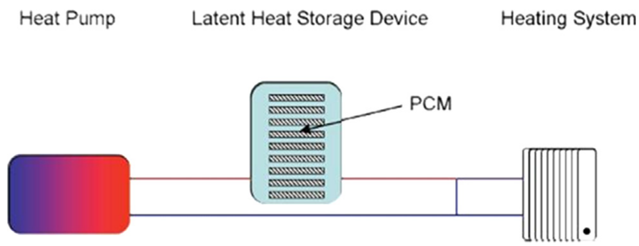

Fig. 3. Diagram of the heat pump system in combination with latent heat storage simulated by Leonhardt and Müller [14].

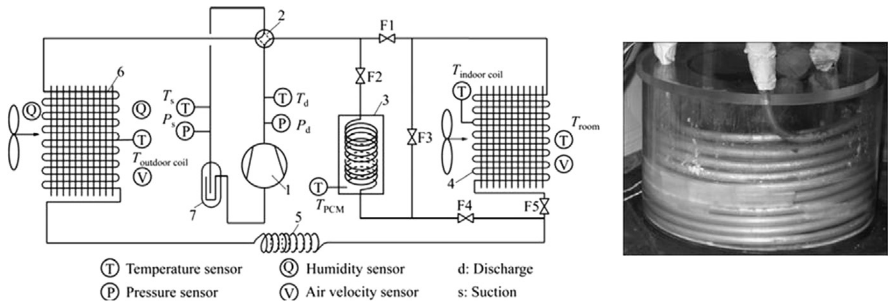

Fig. 4. Schematics diagram of operation for experimental ASHP unit (left) and physical view of PCM heat exchanger (right) evaluated by Jiankai et al. [16]. (1) Compressor, (2) four-way reverse valve, (3) PCM heat exchanger, (4) indoor coil, (5) capillary tube, (6) outdoor coil, and (7) gas–liquid separator; F1–F5 solenoid modulating valves.

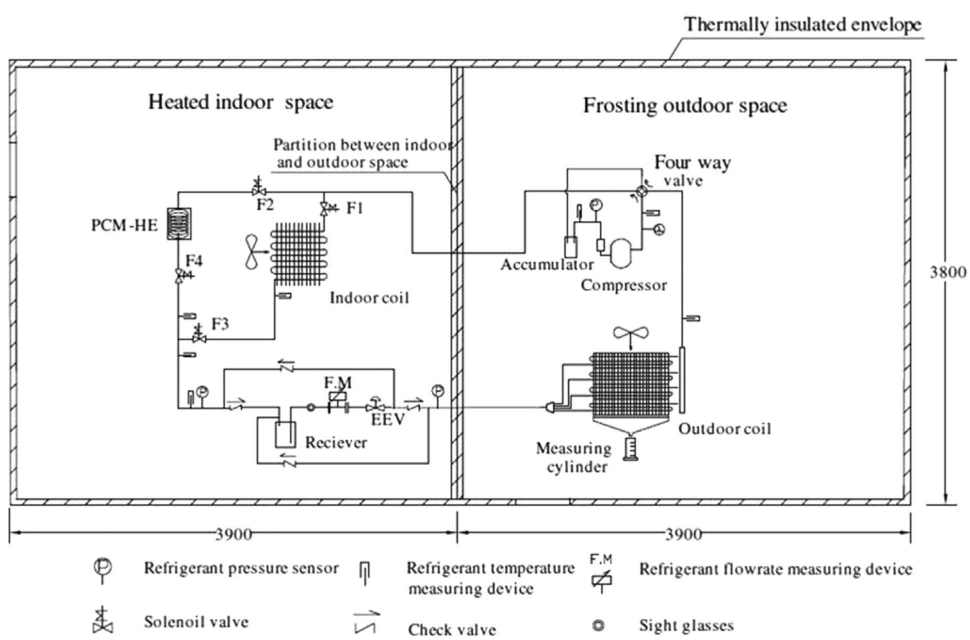

Fig. 5. Schematic diagram of the experimental set-up evaluated by Minglu et al. [17].

The results showed that defrosting duration was shortened by 60% when using the PCM heat exchanger, as compared with that using the conventional defrosting method. The energy consumption for defrosting was also reduced by 48.1% and the COP was slightly higher for the system using the PCM heat exchanger.

Another problem that appears as a consequence of a reverse-cycle defrosting process is that the indoor coil in an ASHP actually acts as an evaporator, thus no heating is provided and indoor air temperature in a heated space can drop. Furthermore, a long period of time is needed until thermal comfort for occupants is achieved again. Minglu et al. [17] (China) studied the use of a PCM storage unit for defrosting in ASHP in order to improve the indoor thermal comfort during the process. A PCM heat exchanger was designed as a thermally insulated shell-and-tube storage unit with the PCM on the shell side and the refrigerant circulating inside the tubes. The PCM used was $CaCl_2 \cdot 6H_2O$ with 29 °C as melting point and 190.8 kJ/kg as heat of fusion. A modified commercial ASHP 6.5 kW heating capacity was tested in this study, installed in a 3.9 m length × 3.8 m width × 2.9 m height environmental chamber (Fig. 5).

Two indices from Fanger's thermal comfort model [18] were analysed in this study: Predicted Mean Vote (PMV) and Percentage Dissatisfied (PPD). The results between the standard defrosting method (reverse-cycle) and the PCM heat exchanger for defrosting were compared. The defrosting time was 36.4% shorter when using PCM heat exchanger, compared to standard method with exactly the same amount of frost accumulated on the outdoor coil. Moreover, the TES based reverse-cycle led to higher indoor air temperature during defrosting process according to the results obtained from the thermal comfort indices, so the indoor thermal comfort was significantly improved.

2.3. Hybrid systems for space heating

Some researchers have studied the use of heat pumps and PCM storage units combined with other energy sources such as solar or ground energy. These systems have also been evaluated when the storage unit is incorporated in a radiant floor to improve the occupant's comfort. All these type of systems are named in this paper as hybrid systems and are explained next.

Mazo et al. [19] (Spain) developed a model to simulate a radiant floor system with PCM in a single-zone building. The PCM was integrated into the radiant floor by being embedded in the concrete material of the slab. The simulated PCM was a granulated compound with 27 °C as phase change temperature. The amount of PCM incorporated in slab materials was 20% in mass of the mortar-PCM composite, which was adjusted to achieve the total shift of the heating energy demand from peak hours to off-peak hours. A case study, in which the floor system was fed by an air to water heat pump, was evaluated using the mathematical model. It was found that the system using PCM was able to meet the heating demand requirements with a practically total shift of the electricity demand time. This effect implies an energy consumption cost savings of nearly 18% compared to the conventional radiant floor system.

Cabrol et al. [20] (UK) carried out a comparative transient simulation analysis for domestic buildings with a floor-embedded heating system coupled to a modern air source heat-pump (ASHP). The TRNSYS model evaluated the effects of heat pump control during off-peak electricity tariff periods within different building typologies. The study also analysed the results when PCM were embedded in concrete floor slab as heat storage. From the results it was concluded that in a highly insulated building, a 20 cm concrete floor slab or a 10 cm concrete slab embedding a PCM melting at 22.5 °C was recommended. Moreover, the latter provided slightly improved temperature stability during heating season and a greater stability during summer, thereby reducing the risk of overheating.

Another application of heat pumps with PCM thermal energy storage is coupling the system to a solar installation. Some authors have done theoretical studies about these systems focusing on the design parameters and the PCM selection. Esen and Ayhan [21] developed a mathematical model based on enthalpy method of a PCM storage tank using cylindrical packages in a solar installation. They found from the study that the PCM, cylinder radius, the mass flow rate, and the inlet HTF temperature must be chosen carefully in order to optimize the performance of the PCM tank. Çomakli et al. [22] also concluded that the selection of the PCM and the contact area between the heat transfer fluid and the PCM are key parameters in the design of the tank.

Kaygusuz [23] (Turkey) carried out an investigation on the performance of an experimental set-up of a combined solar-heat pump system with energy storage in encapsulated PCM for residential heating. Two different systems were tested and compared for heating a 75 m^2 room. Each system was composed by a heat pump connected to solar collectors in either series or parallel way with storage. The first one consisted of a conventional flat-plate solar collector, an energy storage tank filled by PCM as heat storage material, a heat pump with water-to-refrigerant heat exchanger, an air-cooled condenser, a liquid-to-air heat exchanger for direct solar heating and other conventional equipment; the system diagram is presented in Fig. 6(a). The hot water which comes from the collectors first goes to the energy storage tank where it releases some energy to the PCM, and later it is used as heat source by the water-source evaporator. Then it is sent to the solar collectors by water circulating pump. However, at night and on cloudy days, the low temperature water that comes from the evaporator is heated up by the PCM of the energy storage tank, and it flows to the evaporator to be used as heat source. The second system follows the diagram shown in Fig. 6(b). In this case the system combines simultaneously two main components: a conventional solar heating system and a conventional air-to-air heat pump. The heat pump uses ambient air as an energy source while the water-to-air heat exchanger uses solar energy as heat source, and each of these separately gives its energy to the heating load of the building. Thus, the total available energy of the system is the sum of the extracted energies from two different systems: solar system and heat pump. In both cases the storage tank was made of sheet iron and had a diameter of 1.30 m and 3.20 m long. It consisted of a vessel packed in the horizontal direction with PVC cylindrical tubes filled with 1500 kg of $CaCl_2 \cdot 6H_2O$ as PCM. From the experimental results it was obtained that 30 m^2 of solar collectors was needed for both systems in order to satisfy the heating requirements. Moreover, the COP for the series system was substantially higher than the parallel system; the first one presented an average seasonal heating performance of 4.0 while the parallel system reached 3.0.

After the experimental study of the combined solar-heat pump system with energy storage Kaygusuz [24] compared the results with a quasi-steady-state model developed in BASIC language. The results showed that the model agreed well with the experimental results.

During low ambient temperature days the air-source heat pumps suffer from decrease in both heating capacity and COP, and increase in compressor pressure ratio. To minimize this effect, Niu et al. [25] (USA) carried out experiments with a heat pump system which included a PCM heat exchanger and a solar thermal collector. The schematic diagram of the installation is shown in Fig. 7. The PCM storage unit was able to store solar energy for solving intermittence and instability of solar energy, and also acted as the evaporator of the heat pump. The PCM storage unit consisted of three passes of concentric copper tubes. The PCM used was RT6 with a latent heat of 183 kJ/kg and 6 °C as phase change temperature. The PCM was embedded inside the space between the outer tube and the inner tube. The refrigerant flowed inside the inner tube and the heat transfer fluid (water) flowed in the outer tube. A three-dimensional picture of the PCM storage unit is shown in Fig. 7.

The results of this study showed that the COP of the heat pump system rose quickly during the experiments and reached up to 3.9. It was also observed that the PCM acted as a heat transfer buffering medium between water and refrigerant. Nonetheless, the authors concluded that more studies were needed to explore the PCM charging/discharging mechanisms and improve the operation of the PCM assisted thermal system.

Han et al. [26] (China) went further and they incorporated a ground-source heat pump to the solar installation with the PCM thermal energy storage tank, so the system also used the ground as energy source. They developed a MATLAB transient numerical simulation of the whole system to study the role of the LHTES tank as well as the COP of the whole heating system. The diagram of the system proposed in this study is shown in Fig. 8. Since it has three different heat sources (solar, ground and the PCM storage tank) and two heating devices (solar collectors and heat pump), the system is able to operate in various types of configurations. The PCM storage tank can store thermal energy from either the solar collectors or the ground, and the energy can be used either as heat source of the heat pump or to heat directly the room. The authors evaluated the operational characteristic of the system when it operates within the different configurations. The 30 m^2 solar collector system is connected in parallel. The ground-source system utilizes vertical U-tubes of 60 m depth to exchange the heat and is also connected to the system in parallel. The heat pump is a water to water heat pump and the LHTES tank is a $1.0 \times 1.2 \times 1.0$ m^3 tank which uses $CaCl_2 \cdot 6H_2O$ as PCM enclosed in $140 \times 120 \times 70$ mm^3 packages,

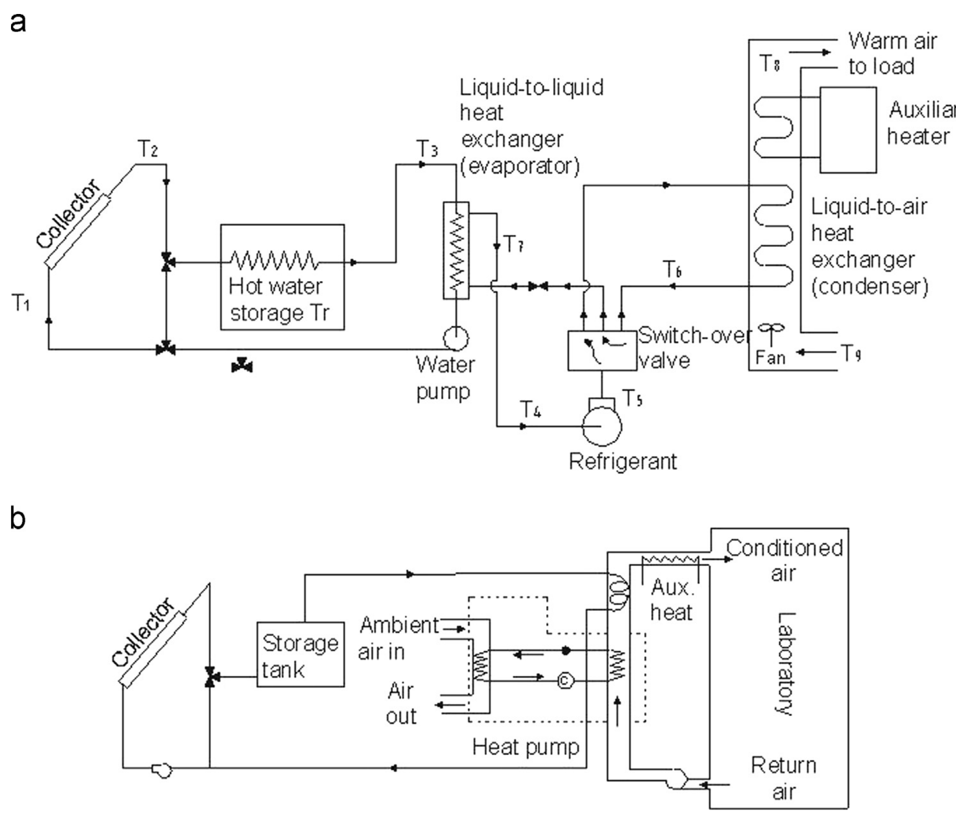

Fig. 6. Diagram of the system studied by Kaygusuz [23]. (a) Solar assisted series heat pump system with energy storage. (b) Solar assisted parallel heat pump system with energy storage.

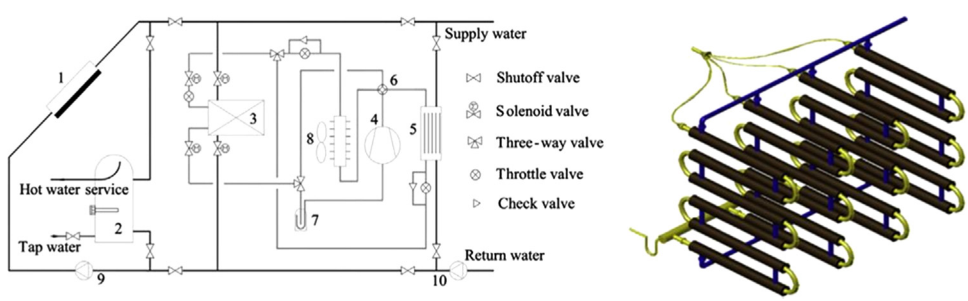

Fig. 7. Schematic diagram (left) and three-dimensional picture of the PCM storage unit evaluated by Niu et al. [25]. (1) Solar collector, (2) thermal storage tank, (3) PCM storage unit, (4) compressor, (5) user side heat exchanger, (6) four-way reversing valve, (7) gas–liquid separator, (8) air side exchanger, (9) heat source pump, and (10) user side pump.

with a total PCM volume of 0.5 m^3. From the simulations it was observed that the LHTES tank plays an important role in the operation of the system. Using this storage device the system can be operated more flexibly, effectively, and stably by the charge and discharge of heat, and the effect becomes especially obvious when the heating load of the building is lower. In this period the system can normally work without heat pump and the daily average COP of the system (daily total supplying heat/consumption of electricity) is higher, being 5.95 the highest value. When higher loads are required, the heating system needs to turn on the heat pump to heat. In this case, the COP of the system decreases to 3.28.

Similarly to the use of heat pumps with LHTES for domestic space heating, the use of ground-source heat pump combined with LHTES systems has also been studied for greenhouse heating. The operational principle implies to couple the PCM storage tank to the condenser of the heat pump while the evaporator is connected to the ground heat exchanger. Benli [27, 28] (Turkey) studied experimentally this type of system using $CaCl_2 \cdot 6H_2O$ as PCM with KNO_3 as nucleation element in a 0.33 m^3 tank volume. The tests were carried out under Turkish winter conditions for heating a 30 m^2 greenhouse. From the results of both studies, it was found that the average heat pump COP and the overall system COP were obtained to be in the range of 2.3–2.8 and 2–3.5, respectively.

Vadiee and Martin [29] (Sweden) performed a qualitative economical assessment software of three different closed greenhouses with integrated TES, with and without short-term daily TES (water and PCM storage tanks) and with seasonal borehole TES using TRNSYS. The evaluation concluded that the peak load has the main impact on the payback time. Moreover, the stratified chilled water tank could be an economical option in closed greenhouses to cover the hourly peak loads respect to PCM storage. The PCM latent heat and the PCM price are two important parameters to consider due to their high impact on the investment costs.

3. PCM storage in heat pump for space cooling

3.1. Thermal energy storage within the air-conditioning cycle

Similarly to the systems described in Section 2.1, PCM storage systems can be put into the compression vapour cycle of an air-conditioning to store cold from the evaporator. This cold can be used then for cooling application without running the compressor.

Fang et al. [30] (China)analysed the thermal behaviour of an ice storage system coupled to an air-conditioning device. As it can be observed in Fig. 9, the storage tank was constructed using a separate heat pipe heat exchanger, which means that one part of the heat exchanger works as refrigerant condenser and the other part as evaporator. The first one is placed before the refrigerant enters into the TES tank and the evaporator part is placed inside the tank working as heat exchanger between the PCM (ice) and the refrigerant. A cold storage tank 1 m high and 0.5 m diameter insulated with polyurethane of 50 mm thickness was connected to the air-conditioning. The evaluation of the results includes performance parameters such as the evaporator and condensation pressures, refrigeration capacity and the COP of the system. From the study it was obtained that the maximum capacity of the tank was 35 MJ. During the charging process the cooling rate was between 3.4 and 3.8 kW with a COP of 2.1–2.3 within the latent heat storage period. In the discharging process the cooling rate was 3.5–3.0 kW.

In a subsequent study Fang et al. [31] also did an experimental investigation on a cold storage air-conditioning system with

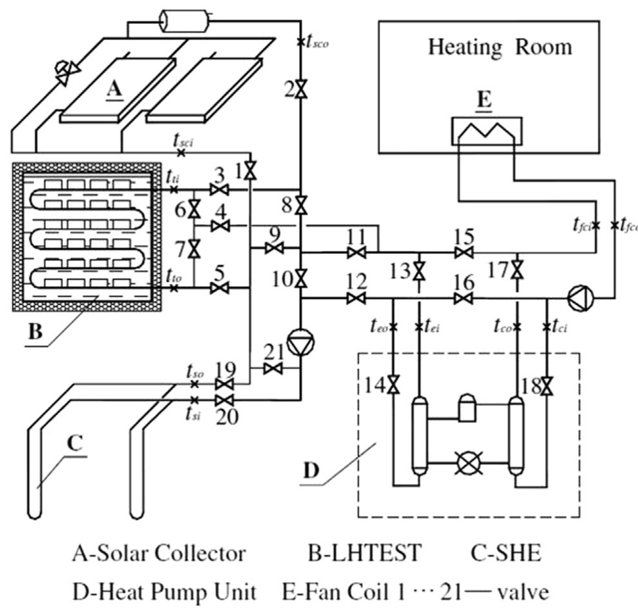

Fig. 8. Diagram of the solar assisted ground-source heat pump heating system with latent heat energy storage tank assessed by Han et al. [26].

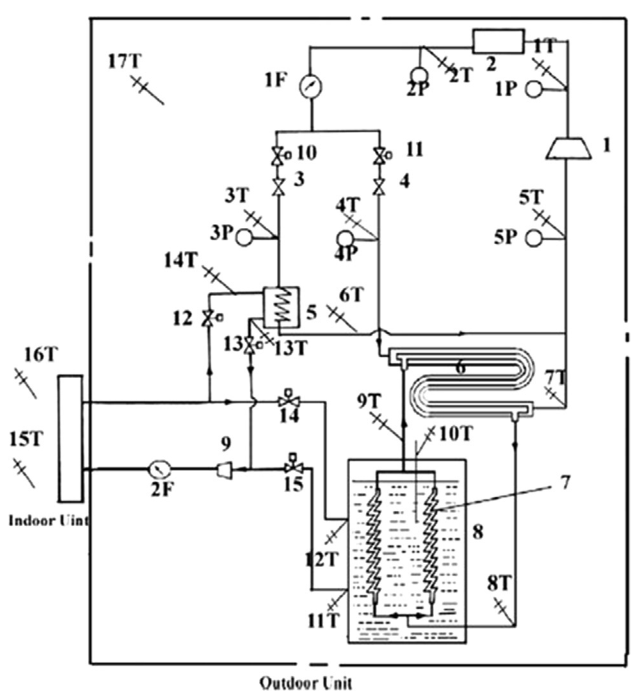

Fig. 9. Schematic diagram of the experimental system evaluated by Fang et al. [30]. (1) Compressor, (2) condenser, (3) and (4) expansion valve, (5) plate evaporator, (6) condensation part of the separate heat pipe, (7) evaporation part of the separate heat pipe, (8) cool storage tank, (9) circulating pump, and (10–15) electromagnetic valve.

spherical ice capsules packed bed. It involved the use of a TES tank with spherical capsules filled with ice in the air-conditioning system. The cold storage tank was 1.2 m height and 0.5 m inside diameter, insulated with 100 mm thickness of polyurethane. It was filled with 183 polymer spherical capsules of 100 mm outside diameter and 1 mm thickness. The advantages of the cold storage tank with the spherical capsules packed bed are the larger heat transfer area and cooling storage capacity, and the more uniform coolant velocity distribution. Besides, it is a flexible system as the number of spherical capsules in the cooling storage tank can be modified according to the cooling load demand. The schematic diagram of the experimental system is shown in Fig. 10. The conventional air-conditioning mode works when valves 14, 19 and 21 are opened. The coolant (25% ethylene glycol solution) is cooled in a plate heat exchanger (number 4) by the refrigeration cycle and the water in the room fan coil circuit is then cooled down through heat exchanger (7). The cool storage mode works when valves 12, 16, 17 and 18 are opened. The coolant is cooled in a plate evaporator (4) and is brought to the cold storage tank. The water inside the spherical capsules releases heat and freezes. The preheater is used to adjust the inlet coolant temperature in the coolant storage tank. When the tank is discharged valves 13, 15, 17 and 19 are opened and the compressor does not need to operate. The coolant circulates inside the tank melting the ice and cooling down the water of the room fan coil circuit through the heat exchanger (7).

They found that in the charging process the COP of the system presented a peak value of 6.4 due to the higher evaporation pressure during start-up period and it varied from 4.1 to 2.1 during the ice latent heat storage period. Moreover, the cold storage rate decreases from 12.3 kW to 6.07 kW during the water sensible heat storage period and gradually reduces to 2.2 kW during the ice latent heat storage, when the water inside the balls solidifies. In the discharging process, the cooling discharge rate varied from 8.5 kW to 3.54 kW.

Another experimental study with cold storage coupled to a refrigeration cycle device was performed by Mettawe et al. [32] (Egypt). The system consists of a TES tank connected to the evaporator part of a refrigeration cycle device, an air handling unit (AHU) and the testing room (Fig. 11). The insulated tank is made of galvanized steel with an internal diameter of 35 cm and a height of 55 cm. The tank was filled with 14 spherical capsules made of copper with a diameter of 10 cm. Each capsule contains 396 g of coconut oil which has a phase change temperature around 25 °C and works as storage material. A comparison of the system efficiency when it works with either 50% fresh air or total return air in the AHU was evaluated. From the results it was concluded that the system does not work with high efficiency when ambient temperature reaches 40 °C, but it works with a temperature range 30–36 °C. Moreover, the efficiency of the system increases by using the total return air.

3.2. PCM energy storage as heat recovery

In summer, air-conditioning systems produce a large amount of condensing heat, about 1.25 times higher than the cooling capacity. Direct discharge into the environment would not only cause a big waste of energy but would also result in thermal pollution with the environment temperature increasing. On the other hand, even in summer months there is daily hot water demand, which is generally obtained by consuming fossil fuels at low energy efficiency. Therefore, the utilization of all or part of the condensing heat recovery can satisfy the demand for daily hot water heating as well as achieve energy savings, contributing to the reduction in CO_2 emissions [33].

The rejected heat from air-conditioning equipment consists of sensible and latent heat, in which sensible accounts for about 15–20% of the total exhausting heat [34]. Gu et al. [35] (China) designed a heat recovery system consisting of two different PCM accumulators installed in series before the condenser of an air-conditioning device in order to store the exhaust heat released by the condenser. This study also evaluated different paraffin wax mixtures, adding lauric acid and liquid paraffin to a paraffin wax, in order to find the better storage material for the studied system, which should have a melting temperature of about 45 °C. The new concept consisted of a conventional air-conditioning system, two heat recovery accumulators and an auxiliary electric water heater (Fig. 12). The latent heat of exhaust is stored by accumulator 2, in which the PCM is paraffin wax with a lower phase change temperature, and the sensible heat of the exhaust is stored by accumulator 1, in which paraffin wax of a higher melting temperature is used as the PCM. When domestic hot water is needed, water from the water tank flows into accumulators 2 and 1 successively, absorbing heat from the hot PCM and supplying hot water over 45 °C. The outlet temperature of accumulator 2 could reach 35 °C, and could then be heated to about 40–45 °C in accumulator 1. The electric water heater is used when the heat recovered is insufficient to satisfy the requirements.

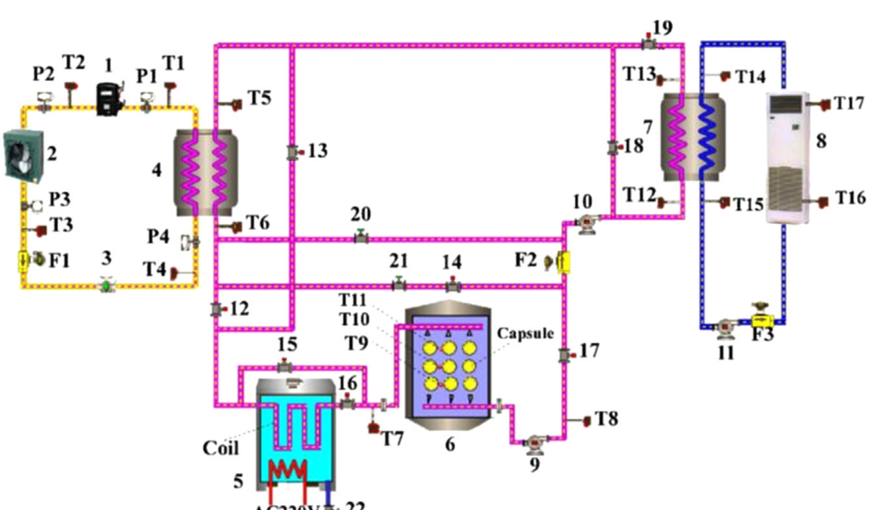

Fig. 10. Schematic diagram of the experimental system studied by Fang et al. [31]. (1) Compressor, (2) condenser, (3) expansion valve, (4) plate evaporator, (5) preheater, (6) cold storage tank, (7) plate heat exchanger, (8) room fan coil unit, (9–11) circulating pump, (12–19) electromagnetic valve, and (20–22) switching valve.

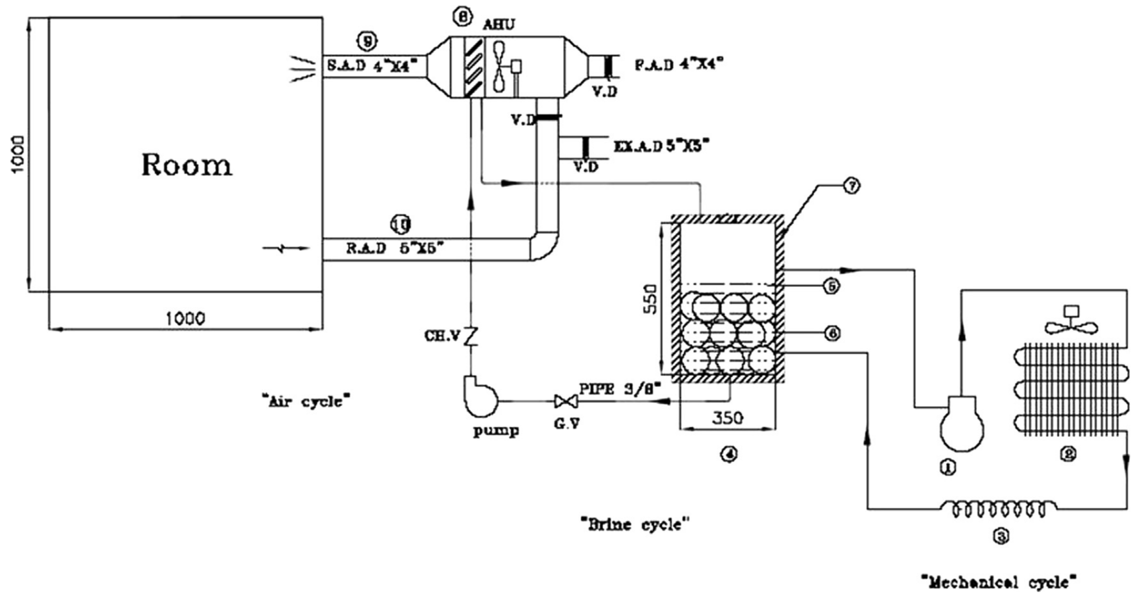

Fig. 11. Experimental set-up of refrigeration cycle with cold storage [32].

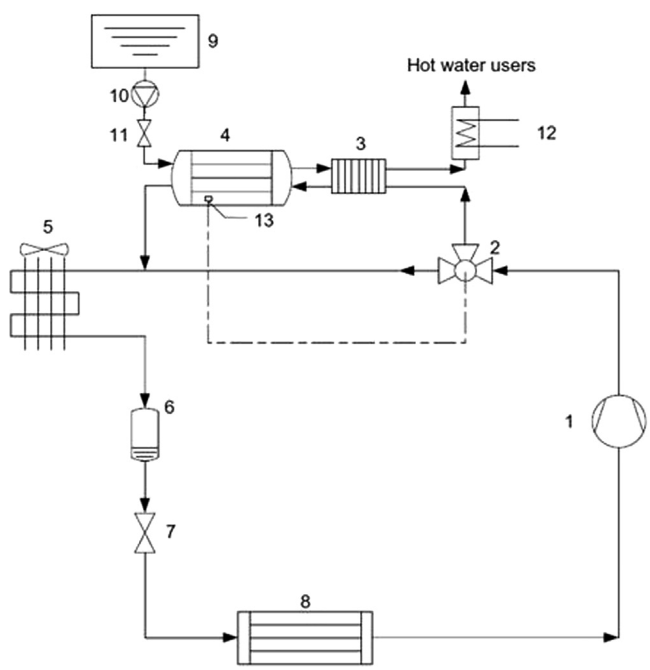

Fig. 12. Schematics of the air-conditioning system with thermal energy recovery devices studied by Gu et al. [35]. (1) Compressor, (2) three-way valve, (3) higher temperature accumulator (accumulator 1), (4) lower temperature accumulator (accumulator 2), (5) cooling tower, (6) liquid storage tower, (7) valve, (8) evaporator, (9) tap water tank, (10) water pump, (11) tap water valve, (12) auxiliary electrical water heater, and (13) temperature sensor.

Through thermodynamic calculations, the integrative energy efficiency ratio (IEER) of the system was calculated and analysed by changing the condensing temperature of the system. It was obtained that the IEER parameter is improved effectively when all the rejected (sensible and latent) heat from the air-conditioning system is recovered. The refrigeration capacity and heat recovery capacity is decreased with the increasing of condensing temperature and the percentage of sensible heat to the total rejected heat is increasing when condensing temperature increases. Regarding to the evaluation of the paraffin PCM, the study concluded that paraffin wax with 40% of liquid paraffin with a phase change temperature of about 44.7 °C was preferred.

Zhang et al. [33] (China) also proposed a heat recovery system for air-conditioning using PCM. Placed before the condenser, the PCM storage tank, with a size of $540 \times 230 \times 250\ mm^3$, was designed for daily hot water preparation. Paraffin wax with 45–48 °C as melting temperature range and 191 kJ/kg as latent heat was used in the bulk PCM tank to store thermal energy. The tank was a shell and tube heat exchanger where the refrigerant and the water flow inside copper tubes. In this study charging and discharging experiments, comparison between air-conditioning with and without thermal storage tank, and relationship between temperature rise and flow rate were analysed. The results show that using the heat recovery system, both compressor power and

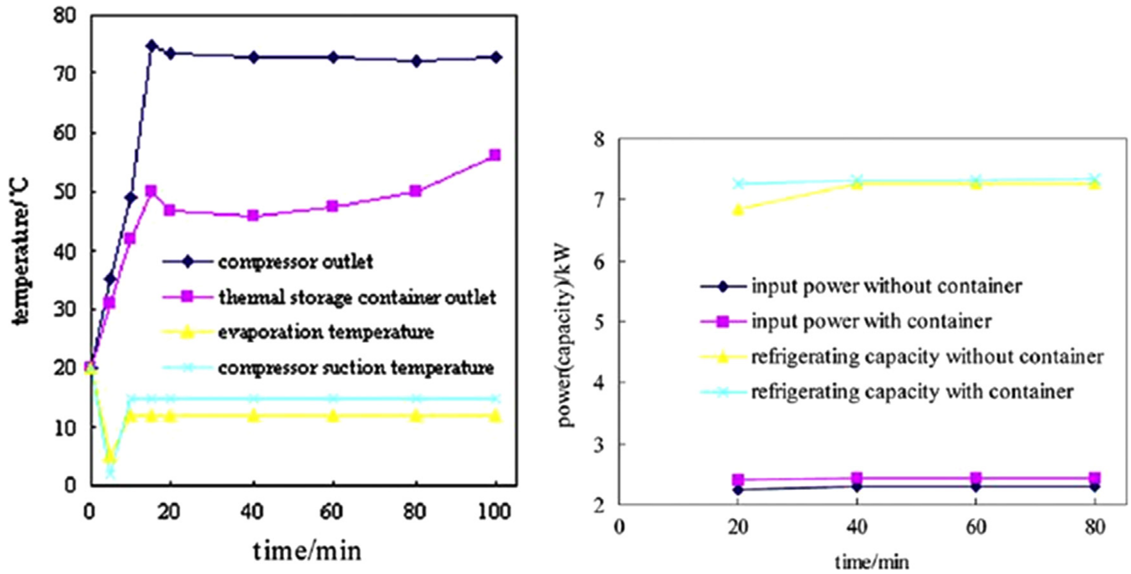

Fig. 13. The effect of thermal storage in the air-conditioning according to the results obtained by Zhang et al. [33]. (a) Air-conditioning operating parameters and (b) comparison of air-conditioning input and output power/capacity. The parameter named "with container" refers to the PCM storage tank.

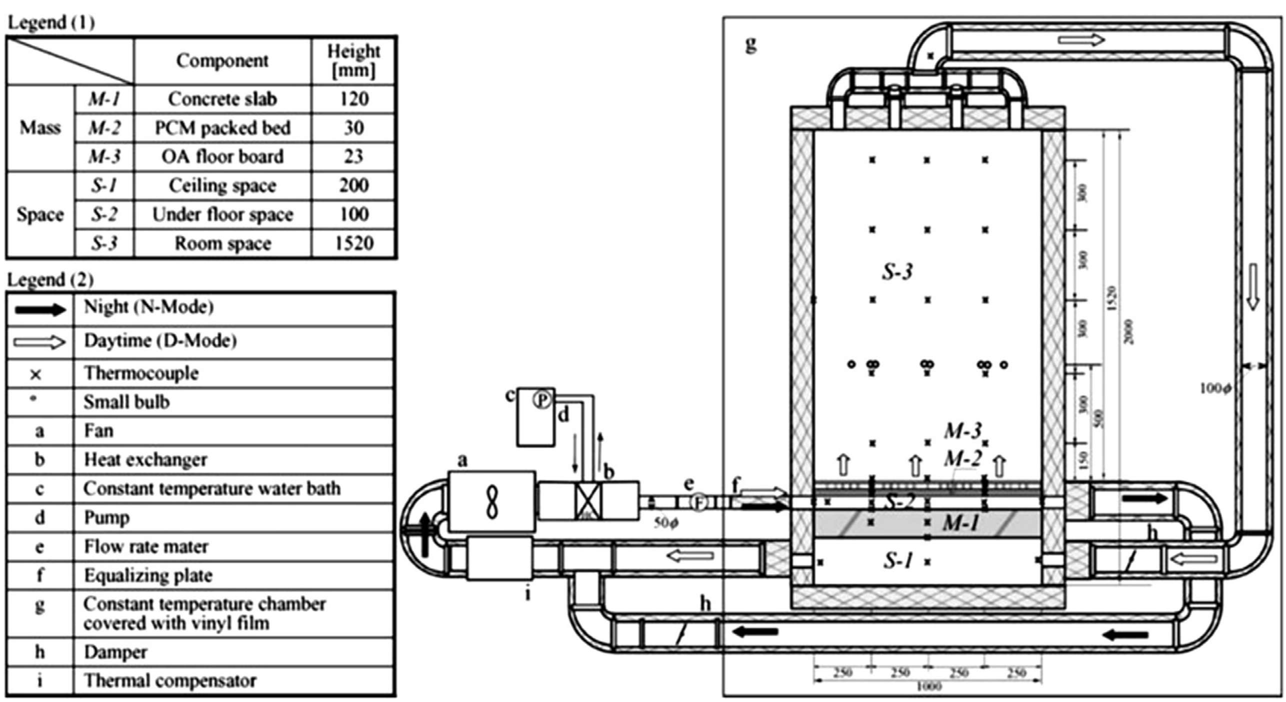

Fig. 14. Schematics of the floor supply air-conditioning system proposed by Nagano et al. [36].

cooling capacity increase while condensing temperature decreases comparing to standard air-conditioning equipment. Fig. 13 presents these results.

3.3. Hybrid systems for space cooling

Similarly to hybrid systems for space heating previously described, there are also some studies which dealt with incorporating the TES device to the air distribution system or cooling radiant floor for space cooling. Nagano et al. [36] (Japan) proposed a floor supply air-conditioning system which used PCM for cold storage. An experimental set-up was built to evaluate the thermal response of the system under office building application. Fig. 14 shows the schematics diagram of the apparatus. The latent heat is stored in PCM that is embedded directly below the floor boards in the form of granules of several millimetres in diameter. This PCM packed bed is permeable to air so it is suitable to be used in floor supply air-conditioning; the PCM should have a melting temperature about 20 °C. During night, circulation of cool air through the under floor space allows cold energy to be charged to the floor. In daytime the cold stored can be used to remove the cooling load in the room. The body of the apparatus is constructed from 100 mm thick heat insulating material. The interior is 1000 mm long and 500 mm deep which gives a floor area of 0.5 m^2. The spaces, shown on the diagram as S-1, S-2 and S-3, simulate the spaces above the ceiling, between the double floor and the room space. The air flowing from the fan is cooled in a duct through a heat exchanger which simulates an air-conditioner. The PCM used in this study was made from foamed glass beads and a mixture between two paraffin waxes, $C_{16}H_{34}$ and $C_{18}H_{38}$, which has a phase change temperature of about 20 °C.

The night operation mode was performed to allow cold charging for 10 h, from 22:00 to 08:00, while the system runs for 12 h during the day. The room temperature was set to 26 °C and the cold water circulating pump (element d in Fig. 14) was turned on to simulate the air-conditioning only if the indoor temperature exceeded that temperature. Experiments were carried out comparing the system with and without PCM, using different air flow rates, and with or without air supply into the room at night. The results show that 89% of the daily cooling demand could be stored during the night in a system that used a 30 mm thick packed bed of granular PCM.

Yamaha et al. [37] (Japan) performed a simulation model where paraffin mixtures containers in the air ducts were used as storage device for air-conditioning equipment. The system was proposed for peak shaving on a summer day taking profit of the special discount tariff that utility companies offer in Japan. PCM mixtures of paraffin waxes in different quantities and with heat of fusion around 90 kJ/kg were considered. During charging operation the air passes through the closed circuit of the PCM storage tank and the air-conditioner (Fig. 15(1)). Once this operation is finished the air-conditioner runs as usual so the air bypasses the PCM storage tank (Fig. 15(2)). The tank is discharged from 13:00 to 16:00 h when the air flows through the storage tank and cools down the inlet temperature of the room (Fig. 15(3)).

The study concluded that for an ordinary office building in Nagoya, 400 kg of PCM for a 73.8 m^2 room (or 5.4 kg PCM/m^2) could maintain a constant room temperature without any cold source operation from 13:00 to 16:00 h. The suitable melting temperature of the PCM was 19 °C.

4. Conclusions

Heat pumps for space heating and cooling are a mature and highly efficient technology which can take advantage of renewable energies. They can also provide energy savings by load shifting when they operate together with thermal energy storage (TES). A review of PCM thermal energy storage systems incorporated in domestic heat pump for space heating and cooling has been presented in this paper. Most of the studies presented are experimental research in laboratory scale, where the thermal behaviour of the whole system is evaluated.

It has been found that the TES systems can be used in different applications. For space heating they can be incorporated within the heat pump cycle for load shifting and as defrosting system of the outdoor unit. The first option is mainly used to reduce the tank size comparing to sensible heat storage tanks while defrosting system is intended to reduce the energy consumption of the device and the defrosting time. There are also some studies which evaluated the incorporation of other devices in the system such as solar collectors or ground source. Some of them are theoretical studies and the experimental ones are focused on the evaluation of the global COP of the system, so further research is needed in order to quantify the effect of the TES inclusion in these systems. For space heating the most used PCM are $CaCl_2 \cdot 6H_2O$ and paraffin which have a phase change temperature within the range 22.5–58 °C. Most of them are used as bulk PCM in shell and tube storage tank.

For space cooling, the TES system can be also incorporated in the refrigeration cycle for load shifting as well as be used for heat recovery. In the first case, charging and discharging capacities of the tanks and the COP are the parameters evaluated by the authors. The PCM used in these systems are ice and coconut oil. On the other hand, heat recovery using PCM storage system uses paraffin waxes with a melting temperature range of 45–48 °C. There are also two studies within space cooling applications which use the TES system in a radiant floor and in air-conditioning ducts for peak load shaving. These studies concluded that the PCM storage is able to operate properly within the system maintaining the indoor temperature during 3–4 h without cooling device. Paraffin waxes are also the PCM used in these studies with a melting temperature of 17–23 °C.

The summary of the studies presented in this paper is shown in Table 1. It includes the application of each system, the reference, the type of study, the PCM used, the type of storage system, the inclusion of any heat transfer enhancement in the PCM, the heat transfer fluid (HTF) used, and the main conclusions of each study.

From this review it can be concluded that further investigation is needed to evaluate the real potential of coupling PCM storage systems to heat pumps in terms of energy savings and CO_2 mitigation, since they present potential on load shifting or peak

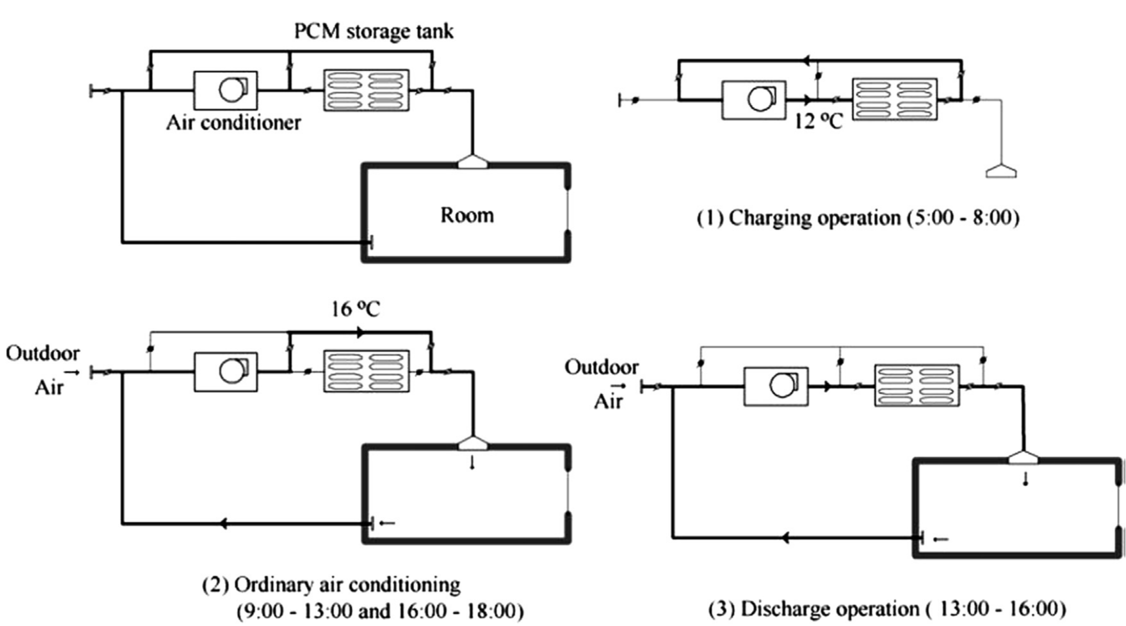

Fig. 15. Diagrams of HVAC system for simulations carried out by Yamaha et al. [37].

Table 1
Summary of the heat pump systems presented in this paper.

Application		Reference	Type of study	Type of PCM	Type of storage	Heat transfer enhancement in the PCM	HTF	Conclusions of the study
Space heating								
TES within the heat pump cycle for load shifting		Hamada and Fukai [11]	Experimental/ Numerical	Ice/Paraffin wax, T_m=49 °C, H_m=180 kJ/kg	Shell and tubes	Yes (carbon fibre brushes)	Water	Reduction in cost and space of the TES tanks
		Agyenim et al. [13]	Experimental	Paraffin RT58	Longitudinally finned tank	Yes (fins)	Water	Reduce the store size by 30%
		Leonhardt and Müller [14]	Numerical	Paraffin, T_m=46.8 °C, H_m=180 kJ/kg	Flat slab PCM packages	No	Water	ON/OFF switching reduction of the heat pump
PCM energy storage as defrosting solution		Daikin [15]	Market product	Polyethylene glycol	Finned tube heat exchanger	Yes (fins)	Polyethylene glycol	Improved heat capacity by about 10% and COP by 50%
		Jiankai et al. [16]	Experimental	$CaCl_2\cdot6H_2O$ with $SrCl_2\cdot6H_2O$	Shell and tubes	No	Refrigerant	Defrosting time is reduced by 60% and energy consumption during defrosting reduced by 48.1%
		Minglu et al. [17]	Experimental	$CaCl_2\cdot6H_2O$, T_m=29 °C, H_m=190.8 kJ/kg	Shell and tube	No	Refrigerant	Defrosting time is reduced by 36.4%
Hybrid systems	Heat pump-radiant floor with TES	Mazo et al. [19]	Numerical	Granulated compound (substance not specified), T_m=27 °C	PCM incorporated in mortar	No	Water	Energy consumption cost saving of nearly 18% compared to conventional radiant floor
		Cabrol et al. [20]	Numerical	(substance not specified) T_m=22.5 °C	PCM embedded in concrete floor slab	No	Water	Slightly improved temperature stability, reducing the risk of overheating
	Solar-heat pump with TES	Kaygusuz [23]	Experimental	$CaCl_2\cdot6H_2O$	PVC cylindrical tubes	No	Water	The series system presented COP of 4 while the parallel system reached 3
		Niu et al. [25]	Experimental	RT6; T_m=6 °C, H_m=183 kJ/kg	Shell and tubes	No	Refrigerant for charging and water for discharging	COP of the system can reach up to 3.9
	Solar- heat pump with ground-source and TES	Han et al. [26]	Numerical	$CaCl_2\cdot6H_2O$	Flat slab PCM packages	No	Water	COP of the whole system is around 3.28
Space cooling								
TES within the air-conditioning cycle for load shifting		Fang et al. [30]	Experimental	Ice	Shell and tubes	No	Refrigerant for charging and water for discharging	Charging: 3.4–3.8 kW; COP: 2.1–2.3 Discharging: 3.5–3.0 kW
		Fang et al. [31]	Experimental	Ice	Spherical capsules packed bed	No	25% ethylene glycol solution	Charging: 2.2 kW-12.3 kW; COP: 2.1–4.1 Discharging: 3.54–8.5 kW
		Mettawe et al. [32]	Experimental	Coconut oil, T_m=24–27 °C	Spherical capsules packed bed	No	20% ethylene glycol solution	System does not work properly under ambient temperatures around 40 °C
PCM energy storage as heat recovery		Zhang et al. [33]	Experimental	Paraffin wax, T_m=45–48 °C, H_m=191 kJ/kg	Shell and tubes	No	Water	Compressor power and cooling capacity increase, and condensing temperature decreases comparing to standard air-conditioning equipment
		Gu et al. [35]	Numerical	Paraffin waxes, T_m about 45 °C,	Shell and tubes	No	Refrigerant for charging and water for discharging	IEER is improved effectively when all the rejected heat is recovered
Hybrid systems	Air-conditioning in radiant floor	Nagano et al. [36]	Experimental	Paraffin waxes, T_m about 20 °C,	PCM embedded in concrete floor slab	No	Air	89% of the daily cooling demand can be stored during the night using granular PCM in the radian floor
	TES in air-conditioning ducts	Yamaha et al. [37]	Numerical	Paraffin waxes, T_m=17–23 °C H_m=90 kJ/kg	Flat slab PCM packages	No	Air	5.4 kg/m^2 of PCM could maintain a constant room temperature without any cold source operation from 13:00 to 16:00 h

shaving. However, the key factor which limits the utilization of these systems is the low heat transfer between HTF and PCM due to the low thermal conductivity of the PCM. This low heat transfer has high effect on the charging time of the PCM storage systems, so an improvement on this parameter will lead to higher energy savings since lower electrical energy would be needed. This also would increase the competitiveness of the PCM versus sensible storage systems.

Moreover, the fluctuating availability of the renewable energies, such solar energy, can be mitigated by the utilization of PCM storage system. So, taking into account that the future energy policies are focused on the increase on the utilization of renewable energies TES systems has to be considered as real and potential technology.

Finally, PCM storage systems have also demonstrated important benefits as defrosting solution in air-conditioning equipment, however, the cost of their implementation comparing to standard solutions is an important barrier for this technology.

Acknowledgements

This work was partially funded by the Spanish government (ENE2011-22722, ENE2011-28269-C03-01, and ULLE10-4E-1305). The authors would like to thank the Catalan Government for the quality accreditation given to their research group GREA (2009 SGR 534).

References

[1] Directive 2012/27/EU on energy efficiency.
[2] European Commission. Energy Efficiency Plan 2011, 8 March 2011.
[3] Directive 2009/28/EC on the promotion of the use of energy from renewable sources.
[4] International Energy Agency. Technology Roadmap. Energy-efficient buildings: heating and cooling equipment, 2011.
[5] Nowak T. European Heat Pump Association predicts market recovery in 2012. Market reports. REHVA Journal, October 2012.
[6] Directive 2002/91/EU on the energy performance of buildings.
[7] Dincer I. On thermal energy storage systems and applications in buildings. Energy Build 2002:34–377-88.
[8] Dincer I, Rosen MA. Thermal energy storage: systems and applications. 1st ed.. . Baffins Lane: John Wiley & Sons, Ltd.; 2002.
[9] Thermal Energy Storage. Technology Brief E17. IEA-ETSAP and IRENA, January 2013.
[10] Mehling H, Cabeza LF. Heat and cold storage with PCM: an up to date introduction into basics and applications. 1st ed.. . Berlin: Springer; 2008.
[11] Hamada Y, Fukai J. Latent heat thermal energy storage tanks for space heating of buildings: Comparison between calculations and experiments. Energy Convers Manag 2005;46:3221–35.
[12] Fukai J, Hamada Y, Morozumi Y, Miyatake O. Improvement of thermal characteristics of latent heat thermal energy storage units using carbon-fiber brushes: experiments and modeling. Int J Heat Mass Transf 2003;46:4513–25.
[13] Agyenim F, Hewitt N. The development of a finned phase change material (PCM) storage system to take advantage of off-peak electricity tariff for improvement in cost of heat pump operation. Energy Build 2010;42:1552–60.
[14] Leonhardt C, Müller D. Modelling of residential heating system using a phase change material storage system. In: Proceedings of the 7th Modelica Conference, Como, Italy, September 20–22, 2009.
[15] IEA. Heat Pump Centre Newsletter, 1990; vol. 8 (2): p. 10.
[16] Jiankai D, Yiqiang J, Yang Y, Xue-dan A. Operating performance of novel reverse-cycle defrosting method based on thermal energy storage for air source heat pump. J Cent South Univ Technol 2011;18:2163–9.
[17] Minglu Q, Liang X, Deng S, Yiqiang J. Improved indoor thermal comfort during defrost with a novel reverse-cycle defrosting method for air source heat pumps. Build Environ 2010;45:2354–61.
[18] Fanger PO. Thermal comfort. 1st ed.. New York: McGraw-Hill; 1973.
[19] Mazo J, Delgado M, Marin JM, Zalba B. Modeling a radiant floor system with Phase Change Materials (PCM) integrated into a building simulation tool: analysis of a case study of a floor heating system coupled to heat pump. Energy Build 2012;47:458–66.
[20] Cabrol L, Rowley P. Towards low carbon homes – a simulation analysis of building-integrated air-source heat pump systems. Energy Build 2012;48:127–36.
[21] Esen M, Ayhan T. Development of a model compatible with solar assisted cylindrical energy storage tank and variation of stored energy with time for different phase change materials. Energy Convers Manag 1996;21:1775–85.
[22] Çomakli Ö, Bayramoglu M, Kaygusuz K. A thermodynamic model of a solar assisted heat pump system with energy storage. Sol Energy 1996;6:485–92.
[23] Kaygusuz K. Investigation of a combined solar-heat pump system for residential heating. Part1: experimental results. Int J Energy Res 1999:1213–23.
[24] Kaygusuz K. Experimental and theoretical investigation of a solar heating system with heat pump. Renew Energy 2000:79–102.
[25] Niu F, Ni L, Yaio Y, Yu Y, Li H. Performance and thermal charging/discharging features of a phase change assisted heat pump system in heating mode. Appl Therm Eng 2013;58:536–41.
[26] Han Z, Zheng M, Kong F, Wang F, Li Z, Bai T. Numerical simulation of solar assisted ground-source heat pump heating system with latent heat energy storage in severely cold area. Appl Therm Eng 2008;28:1427–36.
[27] Benli H, Durmus A. Evaluation of ground-source heat pump combined latent heat storage system performance in greenhouse heating. Energ Build 2009;41:220–8.
[28] Benli H. Energetic performance analysis of a ground-source heat pump system with latent heat storage for greenhouse heating. Energy Convers Manag 2011;52:581–9.
[29] Vadiee A, Martin V. Thermal energy storage strategies for effective closed greenhouse design. Appl Energy 2013;109:337–43.
[30] Fang G, Liu X, Wu S. Experimental investigation on performance of ice storage air-conditioning system with separate heat pipe. Exp Therm Fluid Sci 2009;33:1149–55.
[31] Fang G, Wu S, Liu X. Experimental study on cool air-conditioing system with spherical capsules packed bed. Energ Build 2010;42:1056–62.
[32] Mettawee E, Eldesouki I, Amin S. Experimental study on space cooling with PCM thermal storage. J Appl Sci Res 2012;8:3424–32.
[33] Zhang X, Yu S, Yu M, Lin Y. Experimental research on condensing heat recovery using phase change material. Appl Therm Eng 2011;31:3736–40.
[34] Zhang J. Energy savings technology of refrigeration devices. Beijing: Mechanical Industry Press; 1999.
[35] Gu Z, Liu H, Li Y. Thermal energy recovery of air conditioning system – heat recovery system calculation and phase change materials development. Appl Therm Eng 2004;24:2511–26.
[36] Nagano K, Takeda S, Mochida T, Shimakura K, Nakamura T. Supply of a floor air conditioning system using granular phase change material to augment building mass thermal storage – heat response in small scale experiments. Energy Build 2006;38:436–46.
[37] Yamaha M, Misaki S. The evaluation of peak shaving by a thermal storage system using phase-change materials in air distribution systems. HVAC&R Res Special Issue, 2006; vol. 12: p. 3c.